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Optimal Speed Control of Hybrid Electric Vehicle

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This work was done for the project of modern control.

ABSTRACT

This study compares various control techniques for regulating the speed of Hybrid Electric Vehicles (HEVs) by adjusting the throttle position. Traditional controllers like Proportional-Integral-Derivative (PID) and state feedback methods like Pole Placement Technique (PPT), Observer-Based Controller (OBC), and Linear Quadratic Regulator (LQR). The rigorous method of fuzzy control with PI and PD is also applied. The tuning of the PID controller is specifically examined using Ziegler-Nichols and Hand-Tuning methods to optimize its performance. The primary objective is to achieve smooth throttle transitions and maintain the preferred vehicle speed at zero steady-state error. With comparative analysis, the study uses the best available control strategies that have been deemed effective in better fuel economy, reduced emissions, increased driving safety, and the cost reduction required for manufacturing in HEVs.

INDEX TERMS

Hybrid Electric Vehicles (HEVs), Speed Control, Throttle Adjustment, PID Controller,Ziegler-Nichols Tuning, Hand-Tuning, Pole Placement Technique (PPT), Observer-Based Controller (OBC), Linear Quadratic Regulator (LQR), Fuzzy with PI and Fuzzy with PD.

I. INTRODUCTION

In industrial automation, precise speed control is essential for optimizing manufacturing processes. Additionally, controlling the speed of a vehicle can improve fuel efficiency and limit polluting emissions, which aligns with the global push for greener transportation solutions. Our objective in this paper, will be to implement and compare different solutions for an hev speed control. To do that, we'll start in the next section by a brief literature review on speed control, therefore, we'll into our investigations mainly based on simulation of techniques such as PID Controller with Ziegler-Nichols Tuning and Hand-Tuning , Pole Placement Technique (PPT), Observer-Based Controller (OBC), Linear Quadratic Regulator (LQR), Fuzzy with PI and Fuzzy with PD. After all our simulations, we compare and discuss our results in section four and conclude our paper by presenting some future work that can be done to improve the performance of these simulations.

II. Literature Review

Design of Fractional Order PID Controller for Speed Control of DC Motor

In this paper the authors use a novel approach to control the speed of a DC motor using a fractional order pid controller. This paper studies the control effect of fractional order PID controller in speed control of DC motor and performs a comparative study of classical PID controller and fractional order PID controller for speed control of DC motor. Fractional controller is denoted by $PI^{\lambda} D^{\mu}$ where λ and μ are arbitrary real numbers. From the transfer function of this new controller, the authors were intuitively able to say that the FOPID has more degree of freedom than the conventional PID. It can be expected that the FOPID can provide better performance with proper choice of controller parameters. On the other hand, they also did compute the transfer function of the conventional speed controller for a DC motor. Finally, in the paper they did simulate those controllers with different parameters using different tuning methods and compare the results. From the results of multiple simulations using the step unit function, authors conclude that with λ=1.7 and μ=1.15 all parameters' values such as overshoot, peak time, settle time are reduced and produce best performance compared to the conventional DC motor controller.

Optimal Speed control of hybrid vehicle

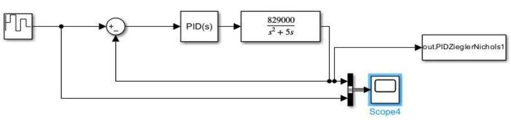
This paper presents a comparative approach of speed control technique for hev by adjusting the throttle position. Like what we're doing in our paper, the author aims to find the optimal technique for speed control. To archive that, they started by providing us a great background on hev and how it works. Then using some transformation, they compute the transfer used in our paper. And finally they did implement various techniques using a set of parameters. From their study, the vehicle is modeled as a nonlinear dynamic system and they used matlab/simulink for all the simulations where they come out with the fact that the LQR approach gives the optimal metrics for speed control.

III. Investigation Details

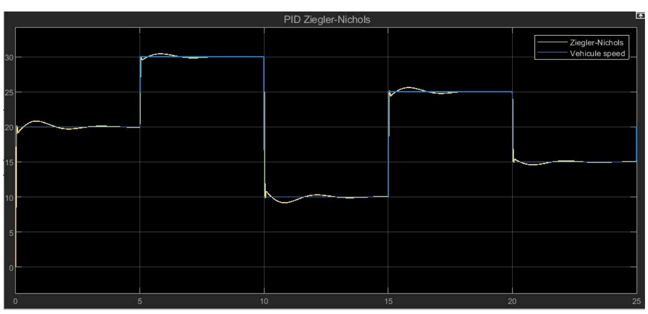
A. PID tuning method

The main paper compares PID controller parameters tuned using the Ziegler-Nichols and Hand-Tuning methods.

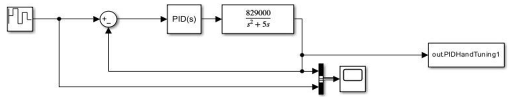
The first method, Ziegler-Nichols, is a heuristic tuning approach that adjusts parameters based on system oscillations. With our case, we set the following parameters $K_P = 1.22 \times 10^{-4}$, $K_I = 3.47 \times 10^{-4}$, and $K_D = 6.8 \times 10^{-6}$, producing a more conservative response.



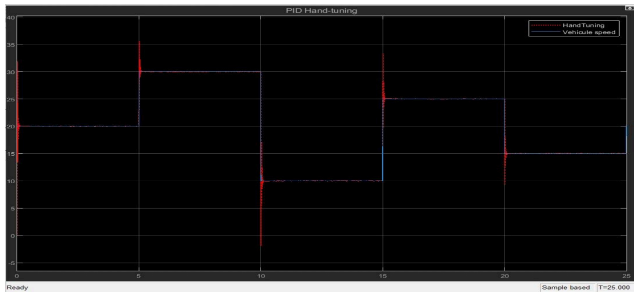
Simulink model of PID controller with plant (Ziegler-Nichol)



The second method, Hand-Tuning is a manual adjustment approach where parameters are fine-tuned through trial and error for desired performance. In our case, it results in $K_P = 0.01$, $K_I = 0.03$, and $K_D = 0.001$, leading to a more responsive but potentially less stable control.

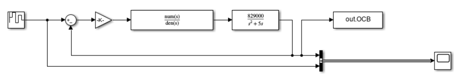


Simulink model of PID controller with plant (Hand-Tuning)

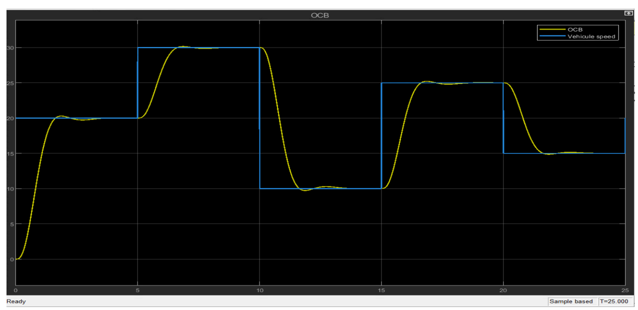


B. Observer-Based Controller (OBC)

In this context, the Observer-Based Controller (OBC) is designed to estimate unmeasurable states of the vehicle system, such as certain internal dynamics, using measurable outputs. In the simulation, the OBC uses these state estimates to inform the control law, allowing for accurate and responsive speed regulation. The transfer function of the vehicle systems is set to Transfer function of the vehicle system: $\frac{V(s)}{\theta(s)} = \frac{8.29\times10^5}{s^2+5s}$, and we found the most suitable gain K = 675.

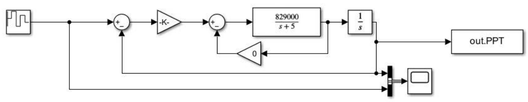


Simulink model of the OCB



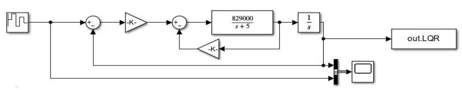
C. Pole Placement Technique (PPT) and Linear Quadratic Regulator (LQR)

The Pole Placement Technique (PPT) involves selecting the poles of the system to achieve desired dynamics. For this study, the parameters are $K_1 = 0.193 \times 10^{-4}$ and $K_2 = 0$, indicating that only one parameter is active, which may lead to a simpler controller but with limited flexibility in achieving optimal performance.

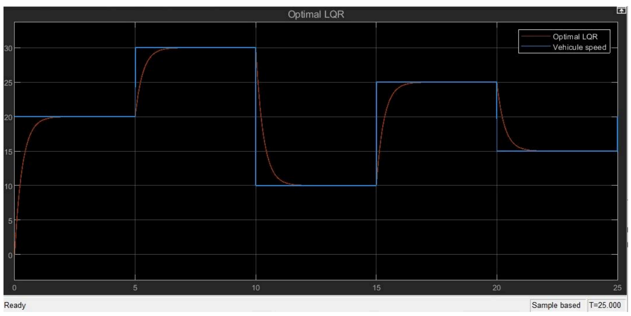


Simulink model of PPT

In contrast, the Optimal LQR technique is a more advanced control strategy that optimizes the performance by minimizing a cost function. The parameter values for this method are $K_1 = 0.3162 \times 10^{-3}$ and $K_2 = 0.1 \times 10^{-3}$, with both parameters being non-zero, indicating a more complex but refined control approach. The Optimal LQR provides a better balance between control performance and stability.



Simulink model of the optimal LQR



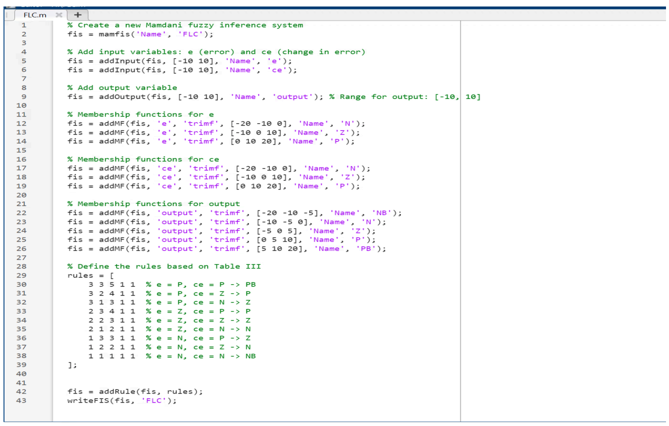
D. Fuzzy controller with PI and PD

The FLC was implemented using a rule-based system, as shown in the Table, with the error (e) and the change in error (ce) as the input variables, both split into three linguistic states: Positive (P), Zero (Z), and Negative (N). The output control actions are defined using fuzzy sets such as Positive Big (PB), Positive (P), Zero (Z), Negative (N), and Negative Big (NB). This rule base manages the system response by mapping e and ce combinations into appropriate control outputs. In the case of the fuzzy PI controller, the output modulates the proportional and integral terms so as to eliminate steady-state error, and in the case of the fuzzy PD controller, the output is linked to the proportional and derivative terms so as to improve transient response. Membership functions were defined with conventional triangular shapes, and Mamdani inference with centroid defuzzification was used to achieve crisp output values. The controller gains were determined experimentally by simulation through subjecting the system to a unit step input and trimming the gains until the system exhibited an optimum response in terms of rise time, stability, overshoot, and steady-state accuracy.

In our case we find $K_P = 1/3$, $K^I = 0.0001$, and $K^D = 0.0001$, and K (FLC gain) = 0.00006.

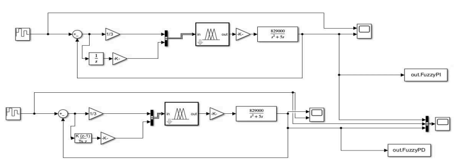
FUZZY RULE BASES FOR FLC

e \ ce	P	Z	N
P	PB	P	Z
Z	P	Z	N
N	Z	N	NB

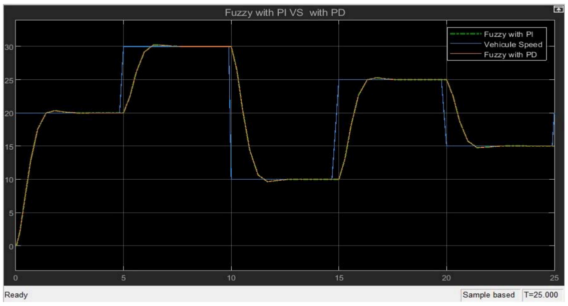


```
% Create a new Mamdani fuzzy inference system
fis = mamfis('Name', 'FLC');

% Add input variables: e (error) and ce (change in error)
fis = addInput(fis, [-10 10], 'Name', 'e');
fis = addInput(fis, [-10 10], 'Name', 'ce');

% Add output variable
fis = addOutput(fis, [-10 10], 'Name', 'output'); % Range for output: [-10, 10]

% Membership functions for e
fis = addMF(fis, 'e', 'trimf', [-20 -10 0], 'Name', 'N');
fis = addMF(fis, 'e', 'trimf', [-10 0 10], 'Name', 'Z');
fis = addMF(fis, 'e', 'trimf', [0 10 20], 'Name', 'P');

% Membership functions for ce
fis = addMF(fis, 'ce', 'trimf', [-20 -10 0], 'Name', 'N');
fis = addMF(fis, 'ce', 'trimf', [-10 0 10], 'Name', 'Z');
fis = addMF(fis, 'ce', 'trimf', [0 10 20], 'Name', 'P');

% Membership functions for output
fis = addMF(fis, 'output', 'trimf', [-20 -10 -5], 'Name', 'NB');
fis = addMF(fis, 'output', 'trimf', [-10 -5 0], 'Name', 'N');
fis = addMF(fis, 'output', 'trimf', [-5 0 5], 'Name', 'Z');
fis = addMF(fis, 'output', 'trimf', [0 5 10], 'Name', 'P');
fis = addMF(fis, 'output', 'trimf', [5 10 20], 'Name', 'PB');

% Define the rules based on Table III
rules = [
    3 3 5 1 1  % e = P, ce = P -> PB
    3 2 4 1 1  % e = P, ce = Z -> P
    3 1 3 1 1  % e = P, ce = N -> Z
    2 3 4 1 1  % e = Z, ce = P -> P
    2 2 3 1 1  % e = Z, ce = Z -> Z
    2 1 2 1 1  % e = Z, ce = N -> N
    1 3 3 1 1  % e = N, ce = P -> Z
    1 2 2 1 1  % e = N, ce = Z -> N
    1 1 1 1 1  % e = N, ce = N -> NB
];


fis = addRule(fis, rules);
writeFIS(fis, 'FLC');
```

Matlab code for Fuzzy rule

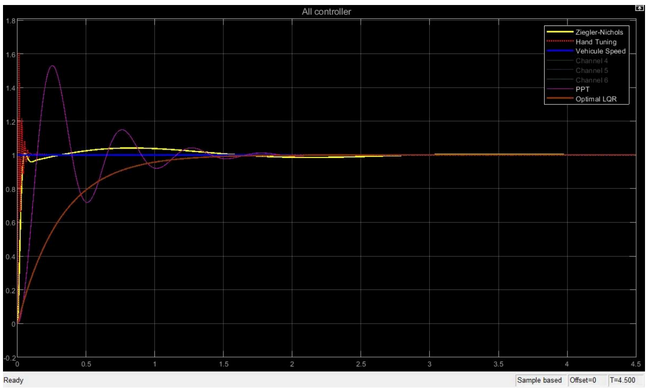


Simulink model Fuzzy with PI and PD



E. Study of the controller with unit step input

By applying a unit step as input, for each of the previous controller, we got the following simulation



IV. Discussion

The PID controller, hand-tuned with the Ziegler-Nichols method, resulted in a fairly conservative response. While it did reduce steady-state error quite effectively, the system exhibited longer rise time and moderate overshoot due to the extreme derivative and integral gains. The Hand-Tuned PID, however, had quicker rise time and more responsive response. But this responsiveness came at the cost of reduced stability and noticeable oscillations in the transient response, which would affect comfort and safety in real-time applications.

The Observer-Based Controller (OBC) effectively regulated internal system dynamics via the estimation of unobservable states. Improved system feedback control accuracy was achieved through this estimation. The OBC showed stable operation with negligible overshoot and smooth steady-state acquisition, indicating robustness in regulating systems whose dynamics are complex or partially unknown.

The Pole Placement Technique (PPT), although easy to implement, showed poor flexibility since it utilized a single active parameter (K_1). The system response, thus, became less sensitive and less accurate compared to other controllers. Although this ease, from a computational standpoint, was beneficial, it curtailed its performance, particularly in fine-tuning transient behavior.

The Linear Quadratic Regulator (LQR) had the best-balanced performance. Optimizing a cost function, it provided very good transient response with very minimal overshoot and no steady-state error. Its two-parameter optimization enabled very precise control, and it was a very suitable candidate for real-time HEV applications where performance and energy efficiency have to be compromised.

The Fuzzy Logic Controllers (FLCs)—with both PI and PD implementations—provided a flexible rule-based control mechanism. The FLCs employed the fuzzy rule base provided in the Table to reason out control actions from error and change-in-error inputs. The fuzzy PI controller possessed satisfactory steady-state performance but a relatively slower response compared to the PD variant. The fuzzy PD controller, however, delivered a sharper, quicker response to the step input with minimal overshoot, but with increased sensitivity to steady-state drift. Values for the fuzzy controllers were obtained through iterative tuning to keep best behavior. While less formally mathematical than LQR, the fuzzy controllers gave intuitive and responsive control that was suitable to the nonlinear system dynamics. In brief, the LQR controller performed the best overall, especially in optimization and smooth transient response. The OBC and fuzzy PD controllers followed closely with good adaptability and control quality. While the PID and PPT methods were good baselines, their weakness was revealed under dynamic conditions.The simulation results verify that more advanced control methodologies like LQR and FLCs can bring improved performance to HEV throttle control

V. CONCLUSION

This article presented a comparative study of various control techniques for throttle control of Hybrid Electric Vehicles (HEVs) in response to a unit step input. Both classical and modern control techniques—namely, PID (Ziegler-Nichols and Hand-Tuned), Observer-Based Control (OBC), Pole Placement Technique (PPT), Linear Quadratic Regulator (LQR), and Fuzzy Logic Controllers (FLCs)—were implemented and compared through simulation models.

The results showed that while traditional PID controllers are simple and effective for straightforward control tasks, their performance is sub-optimal without careful tuning. The LQR controller gave the best overall trade-off between speed, stability, and steady-state accuracy and was therefore found to be highly suitable for HEV applications where optimal dynamic performance is required. The OBC provided stable control via estimation of internal states, while fuzzy PI and PD controllers showed good adaptability to non-linear dynamics and offered a flexible alternative, especially in cases where system modeling is challenging.

Lastly, the study underlines the necessity to select control strategies based on the specific requirements of the vehicle system, such as performance, computational complexity, and robustness. The research in the future can be expanded to hybrid control architectures that combine the strengths of different approaches for even greater levels of performance and efficiency in HEV systems.

VI. REFERENCES

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